原始惑星系円盤の光蒸発

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Nakatani et al (2018a, ApJ, 857, 57)
Nakatani et al (2018b, ApJ, 865, 75)

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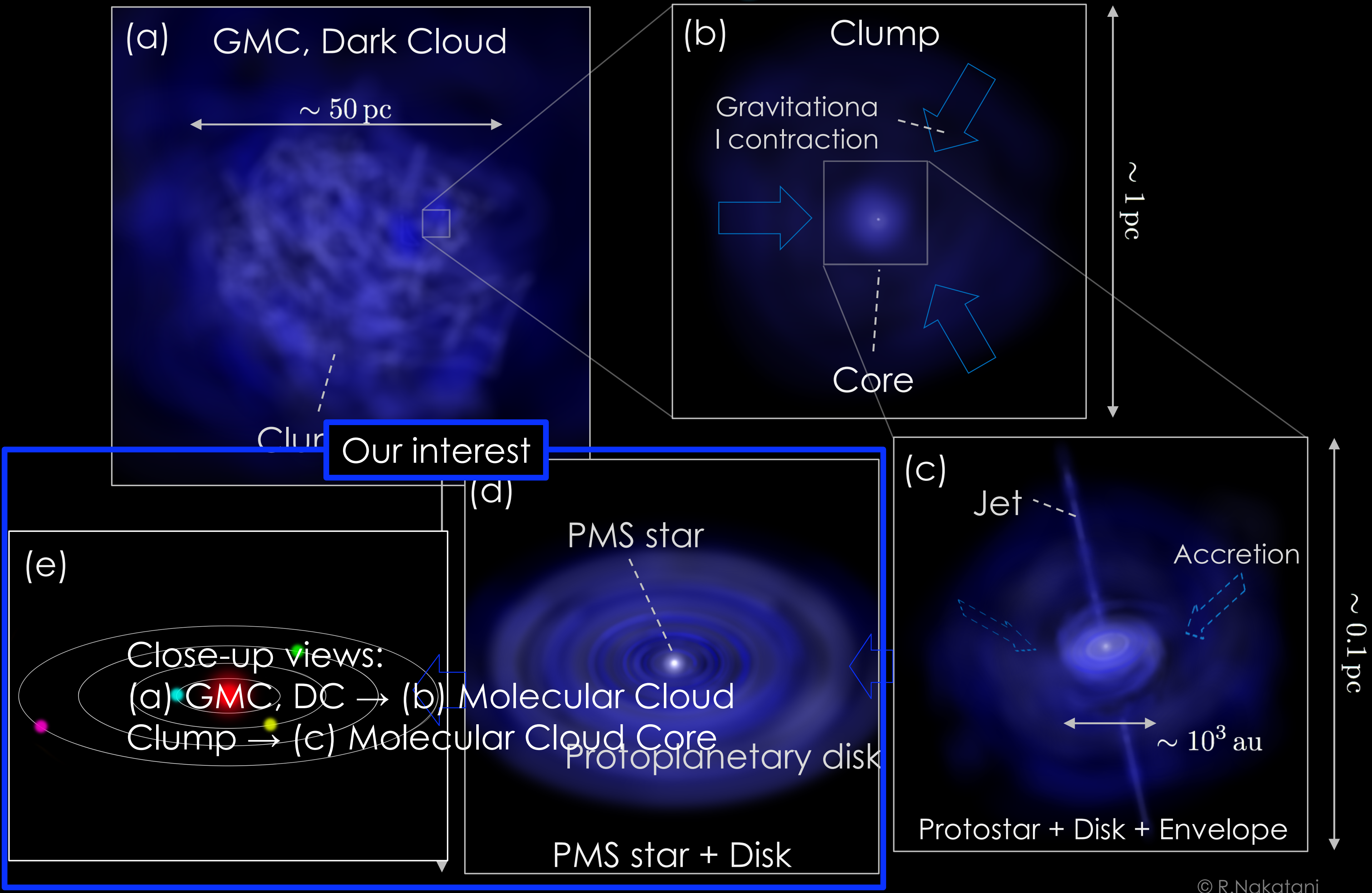
Outline

1. 円盤寿命と光蒸発の関連についてざっくりレビュー
2. 最近の光蒸発研究（Nakatani+18a,bなど。今後の展望を織り交ぜながら。）

Introduction: Stellar-system Formation



(a) GMC, Dark Cloud

$\sim 50\,\mathrm{pc}$

Clun

(b) Clump

Gravitational contraction

Core

$\sim 1\,\mathrm{pc}$

(c)

Jet

Accretion

$\sim 10^3\,\mathrm{au}$

Protostar + Disk + Envelope

$\sim 0.1\,\mathrm{pc}$

Our interest

(d)

PMS star

Protoplanetary disk

PMS star + Disk

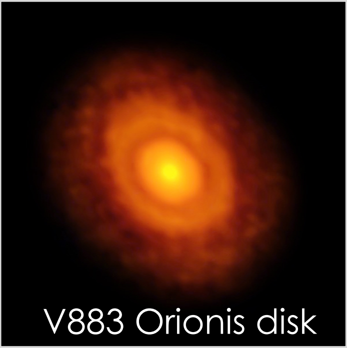
(e)

Close-up views:

(a) GMC, DC → (b) Molecular Cloud Clump → (c) Molecular Cloud Core

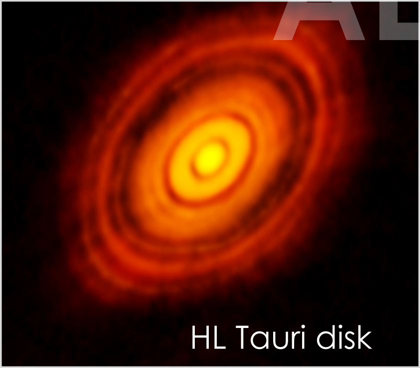
Protoplanetary Disk (PPD)

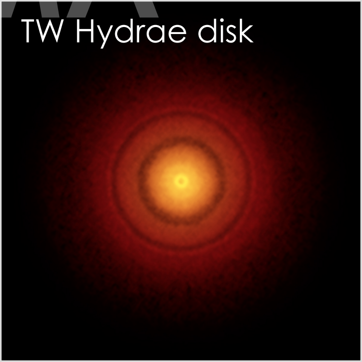
- Geometrically thin Keplerian disk around a young star
- Main components: Gas/Dust
- Birthplace of planets

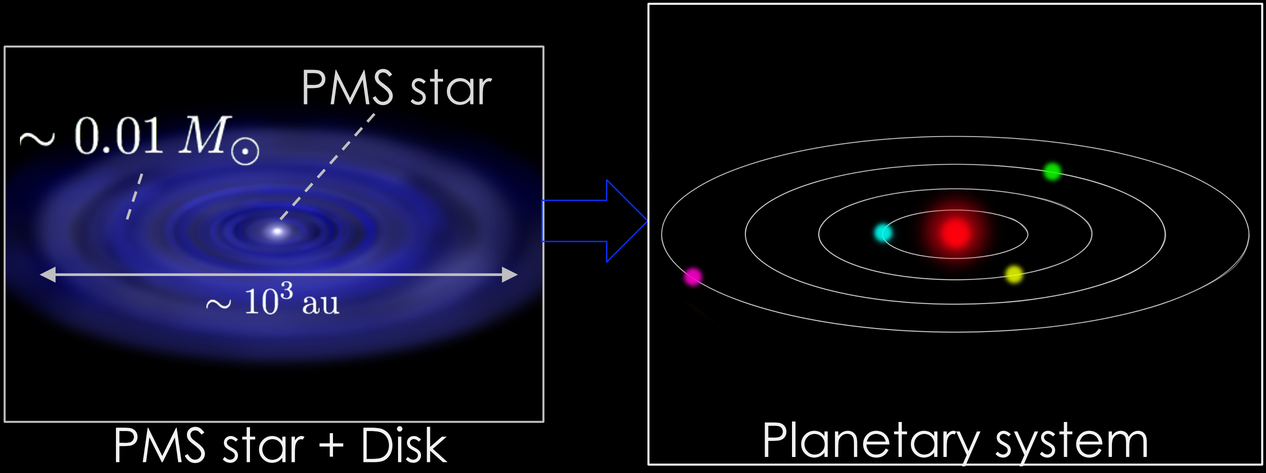


ALMA

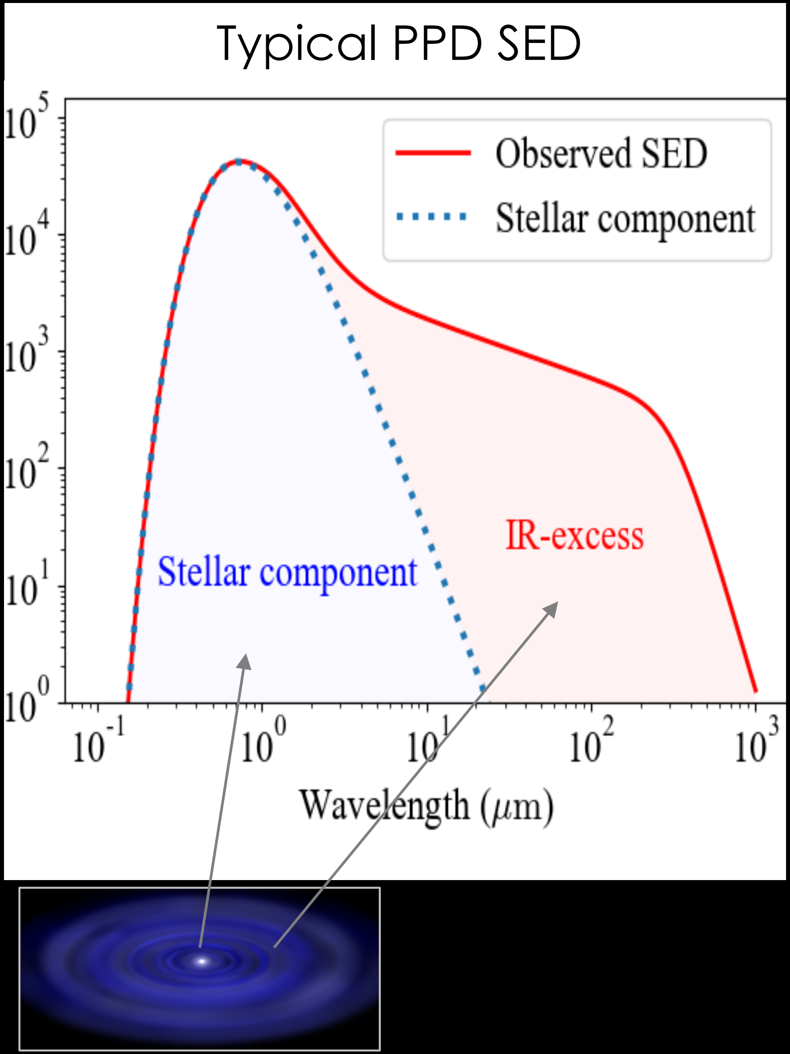
http://www.almaobservatory.org/press-room/press-releases/

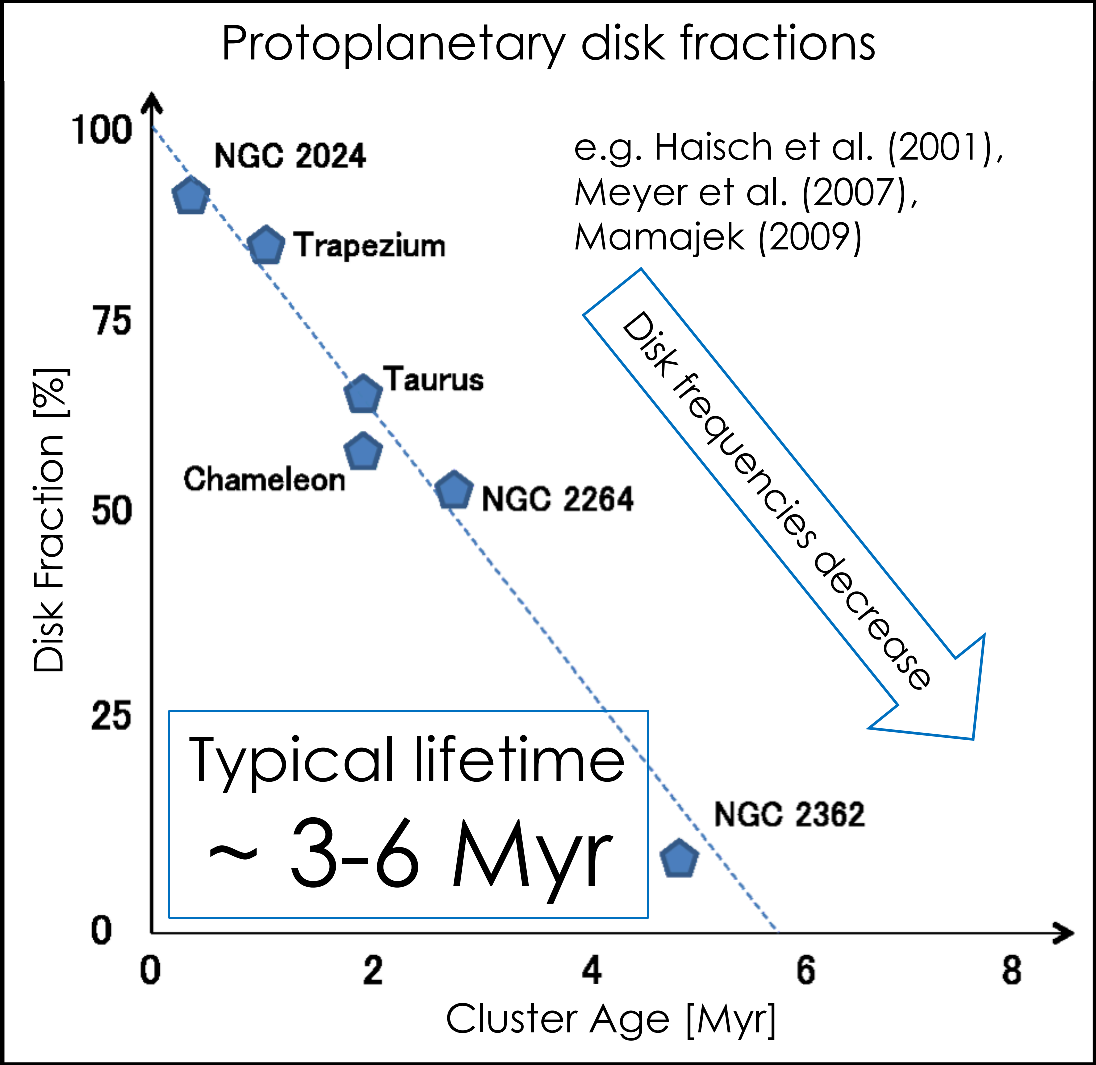






Lifetimes of Protoplanetary Disks


Typical PPD SED


Protoplanetary disk fractions

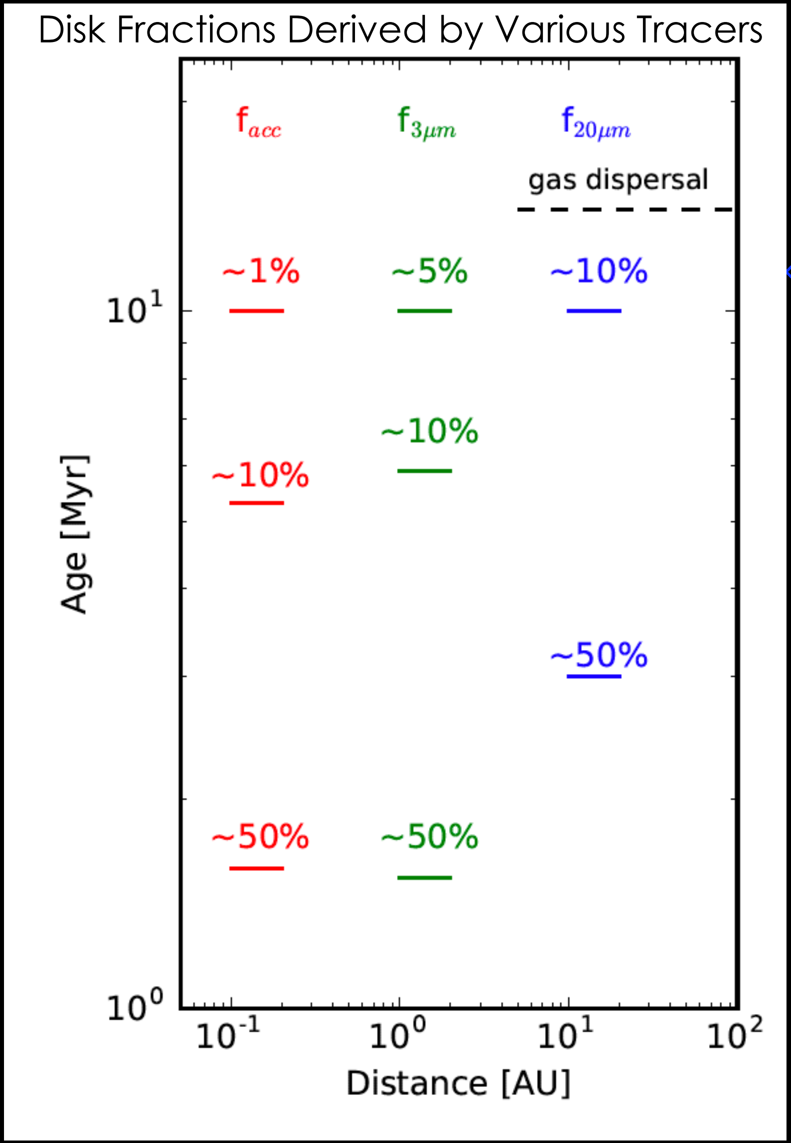
e.g. Haisch et al. (2001),
Meyer et al. (2007),
Mamajek (2009)

Disk frequencies decrease

Typical lifetime
~ 3-6 Myr

*** Disk Fraction = (disk-bearing members in a cluster) / (total number of members)

Disk Fractions with Other Tracers



Ercolano & Clarke (2017)

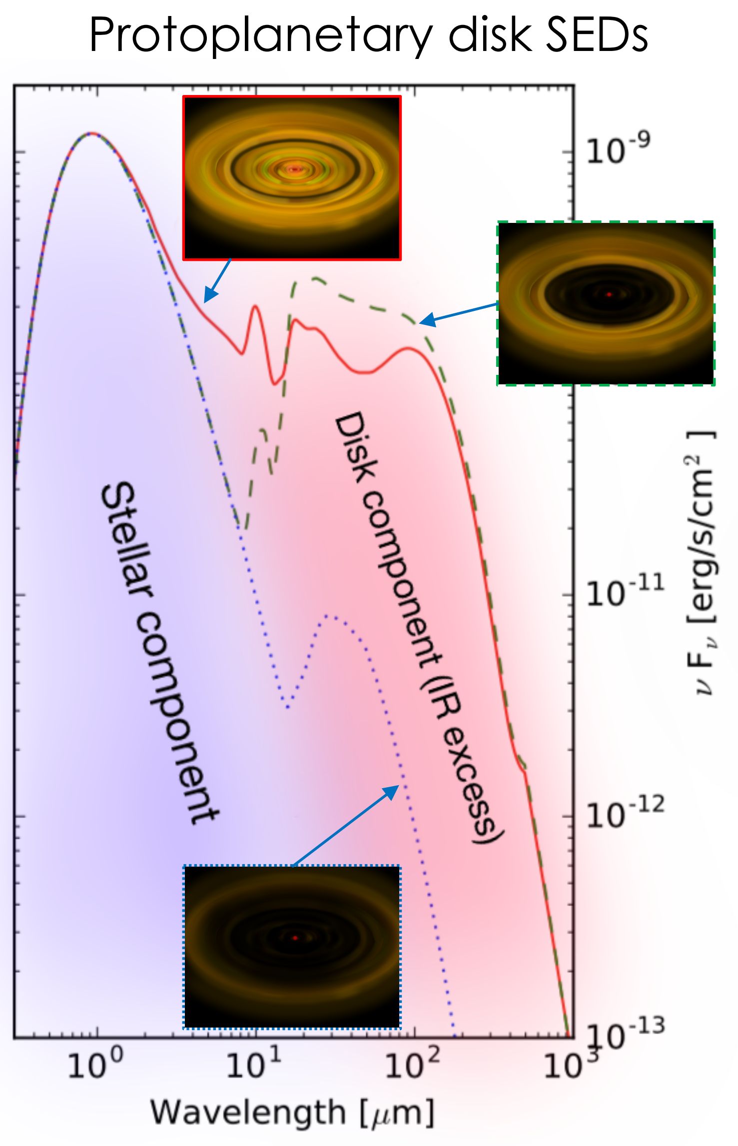
Ha, NIR: disk medium at ~0.1au
MIR: dust disk at ~1au
FIR: dust disk at ~10au
***OI* 63μm**: gas disk at ~10-100au

- e-folding times:
  - **2-3Myr** (Gas, NIR, MIR)
  - **4-6Myr** (FIR)
- Gas signature is not significant in**10-20 Myr**-old disks (e.g., Dent+13)

Bulk mass of both ***Gas and Dust disks*** disperse within **~ 10 Myr**

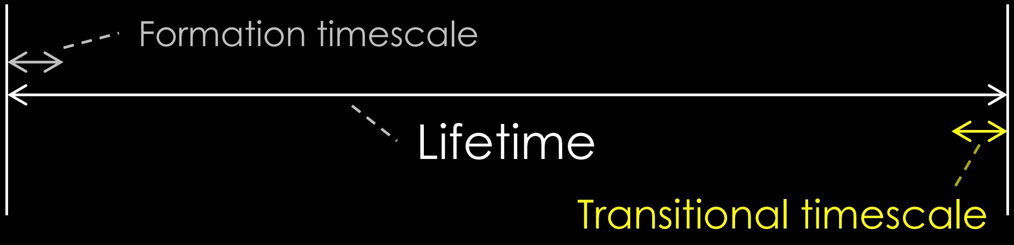
Transitional Disks

—— Objects caught in the act of dispersal ——



Ercolano & Clarke (2017)

- **< 10 %** of PPDs: NIR and/or MIR deficit + MIR and FIR excess (e.g., Strom+89, Furlan+09) → **Transitional Disks**
- Disks clear in an **inside-out** manner.
- The transition time is **~ 10^5 yr**



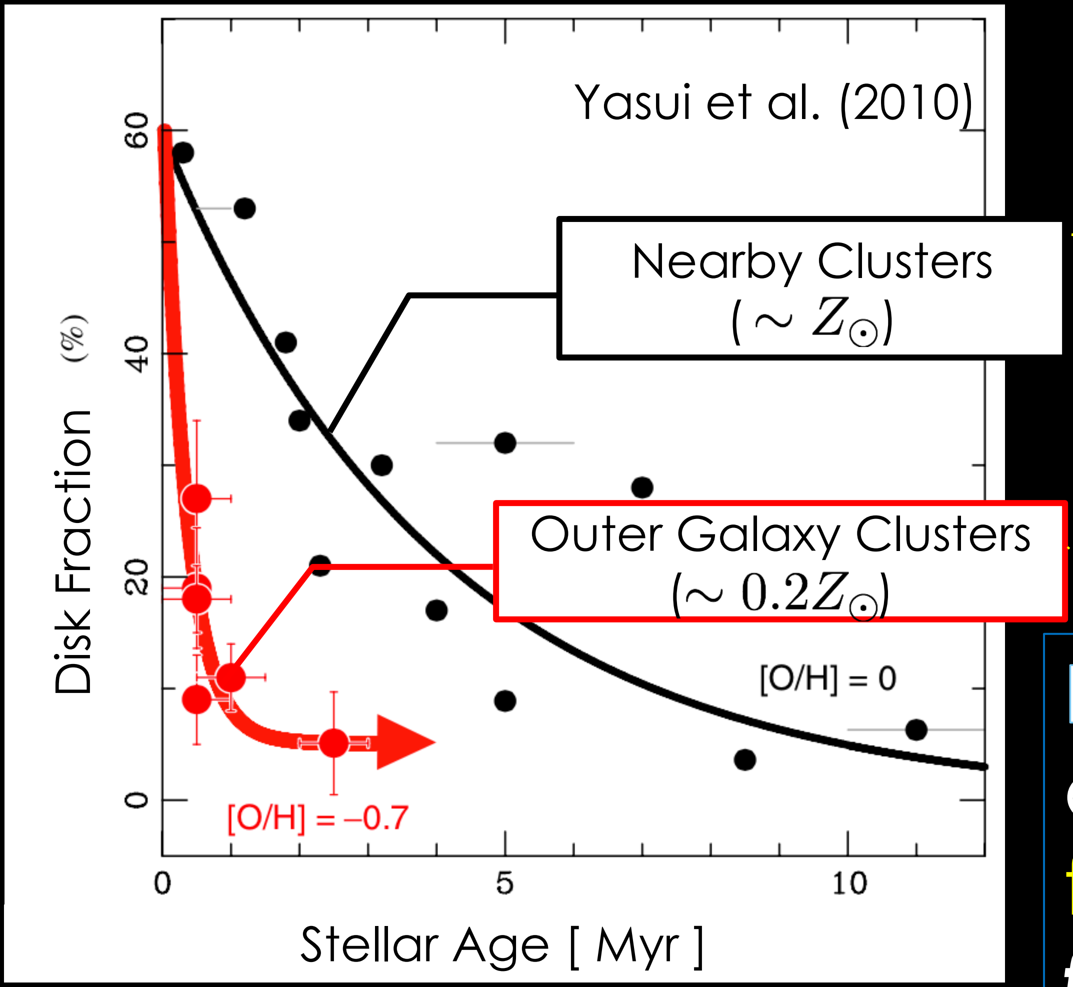
Formation timescale

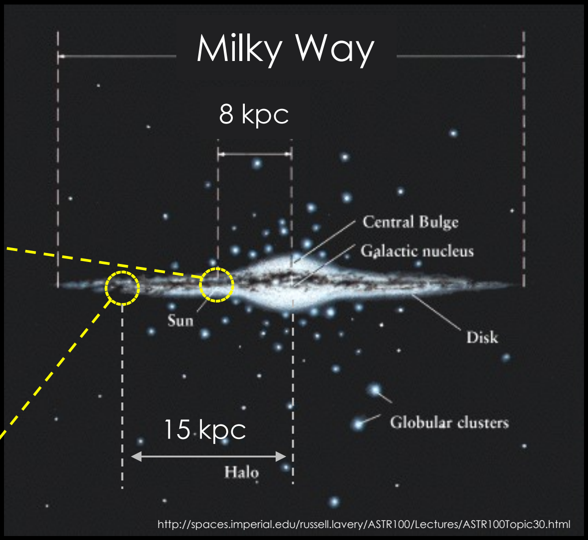
Lifetime

Transitional timescale

Disk dispersal is **very rapid** at the last stage.

Metallicity Dependence of Lifetimes





http://spaces.imperial.edu/russell.lavery/ASTR100/Lectures/ASTR100Topic30.html

Low Z environments may faster disk dispersal ***for some reason***.

Significances of Dispersal Time

Observational suggestions

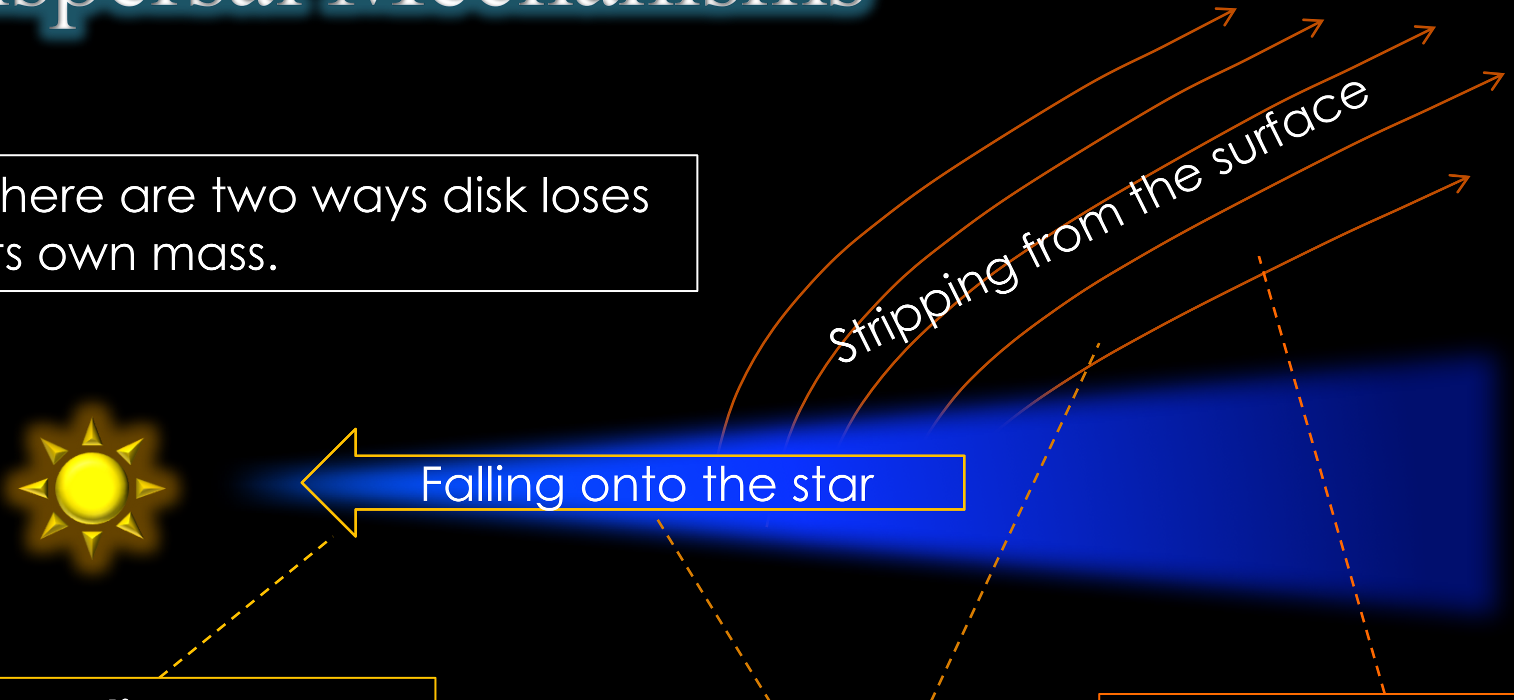
- Gas, dust disk dispersal ***< 10Myr***
- ***10^5 yr transition*** timescale
- ***Short lifetimes*** in low-Z environments

Significances

- Limiting gas giant ***planet formation timescale***
- Constraining ***initial configuration*** of planetary systems and debris disks
- Suggesting conditions for ***planet-formable environments***
- Applying to disk evolution/planet ***formation in general metallicity environment***

Dispersal Mechanisms

There are two ways disk loses its own mass.



- **Accretion** (e.g. Shakura & Sunyaev 1973, Lynden-Bell & Pringle 1974)

Angular momentum transfer due to viscous friction → Materials fall

- **MHD winds** (e.g. Suzuki & Inutsuka 2009, Bai & Stone 2013)

Magneto-hydrodynamical effects (MRI, magneto-centrifugal force) → Winds, driving accretion

- **Photoevaporation** (e.g. Hollenbach et al. 1994, Gorti & Hollenbach 2009)

Irradiation → Thermally driven winds

They are developing areas of the research

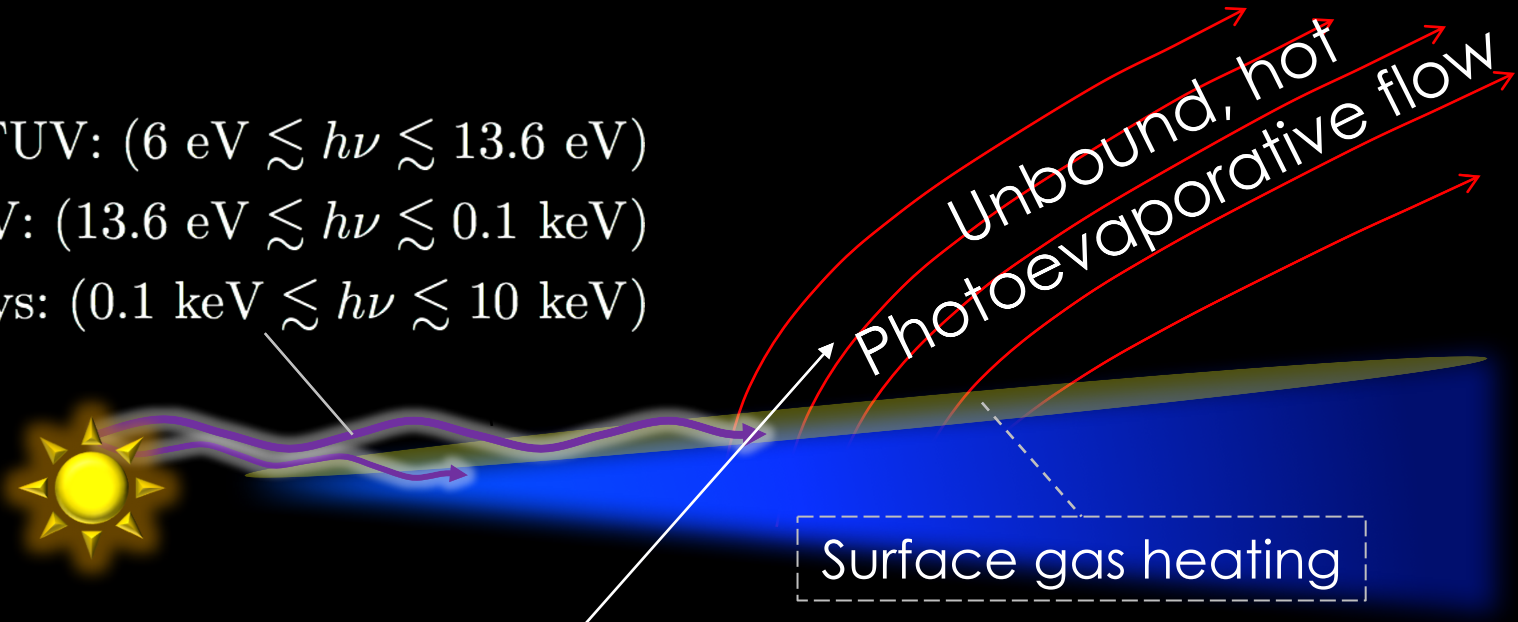
Photoevaporation

e.g., Bally & Scoville (1982); Shu et al. (1993), Hollenbach et al. (1994)

FUV: $(6\ \mathrm{eV} \lesssim h\nu \lesssim 13.6\ \mathrm{eV})$

EUV: $(13.6\ \mathrm{eV} \lesssim h\nu \lesssim 0.1\ \mathrm{keV})$

X-rays: $(0.1\ \mathrm{keV} \lesssim h\nu \lesssim 10\ \mathrm{keV})$



Unbound, hot Photoevaporative flow

Surface gas heating

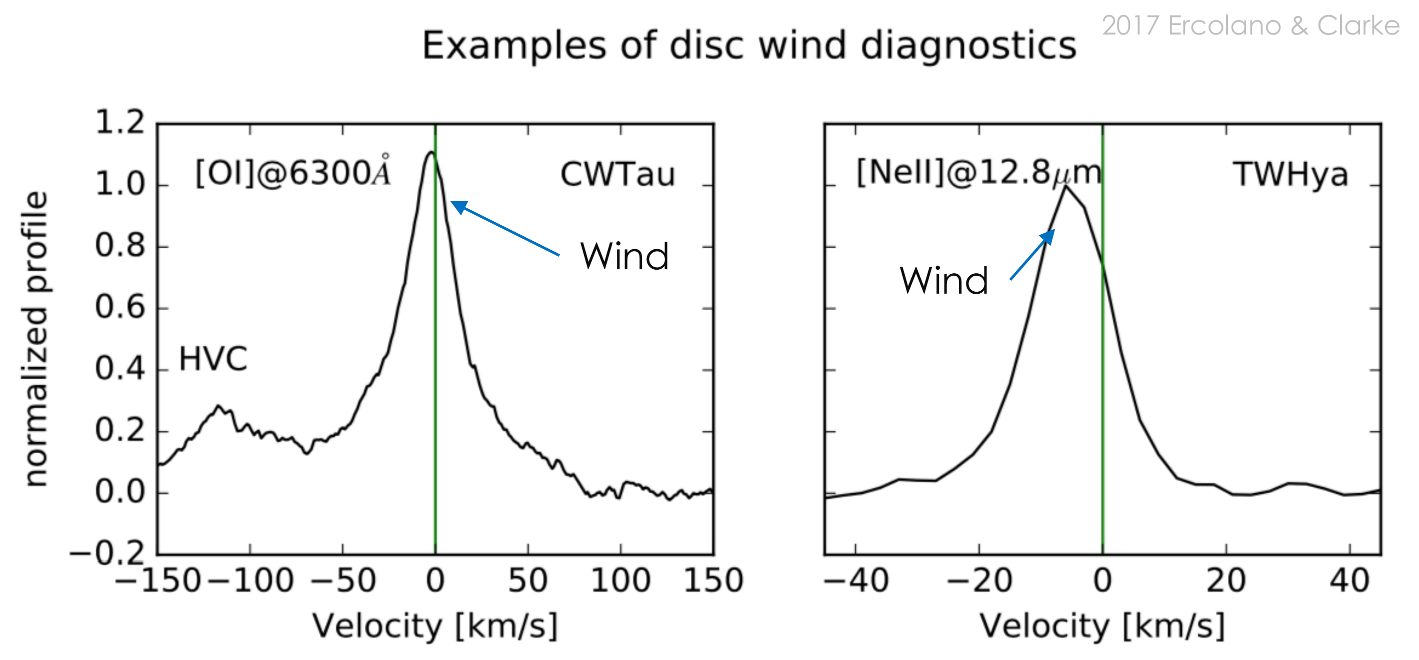
$$\frac{(\text{gravitational energy})}{(\text{thermal energy})} = \frac{GM_*}{rc_s^2} \lesssim 1$$

$$\Leftrightarrow r \gtrsim \frac{GM_*}{c_s^2} \sim 10\ \mathrm{AU} \left(\frac{M_*}{M_\odot}\right)\left(\frac{T}{10^4\ \mathrm{K}}\right)^{-1}$$

Typical mass loss rate (photoevaporation rate): $10^{-10} - 10^{-8}\ \mathrm{M_\odot\ yr^{-1}}$

Observational Signatures: Blue-shifted lines

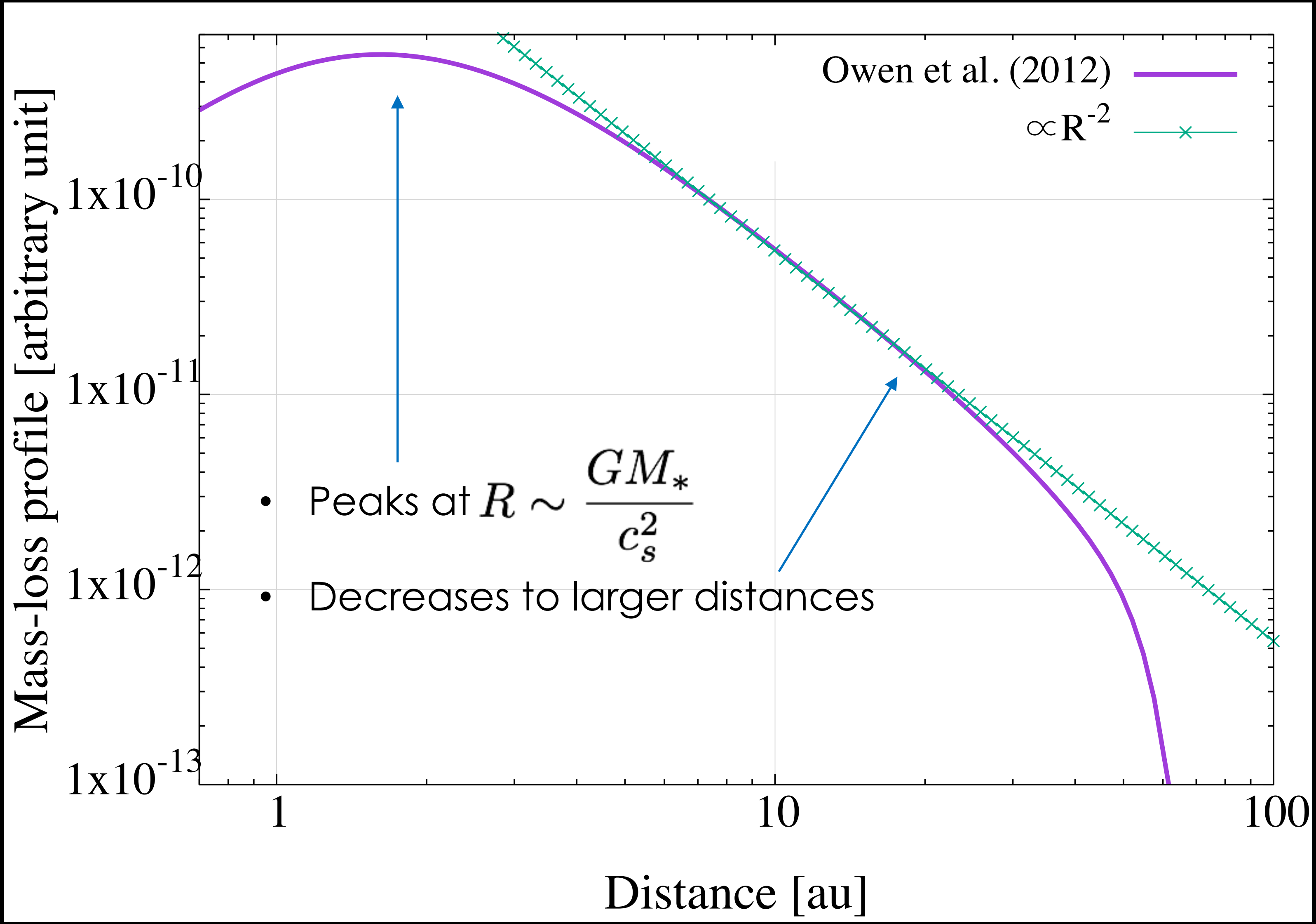
(e.g., Pascucci et al. (2011), Siman et al. (2016), Ercolano & Clarke (2017)



2017 Ercolano & Clarke

- [OI] and [NeII] lines are considered to trace photoevaporative winds (and/or MHD winds).
- Slow (< 30 km/s) and narrow (FWHM < 40 km/s) blue-shifts of NeII emission are consistent with photoevaporation models (Alexander, 2008b; Ercolano and Owen, 2010)

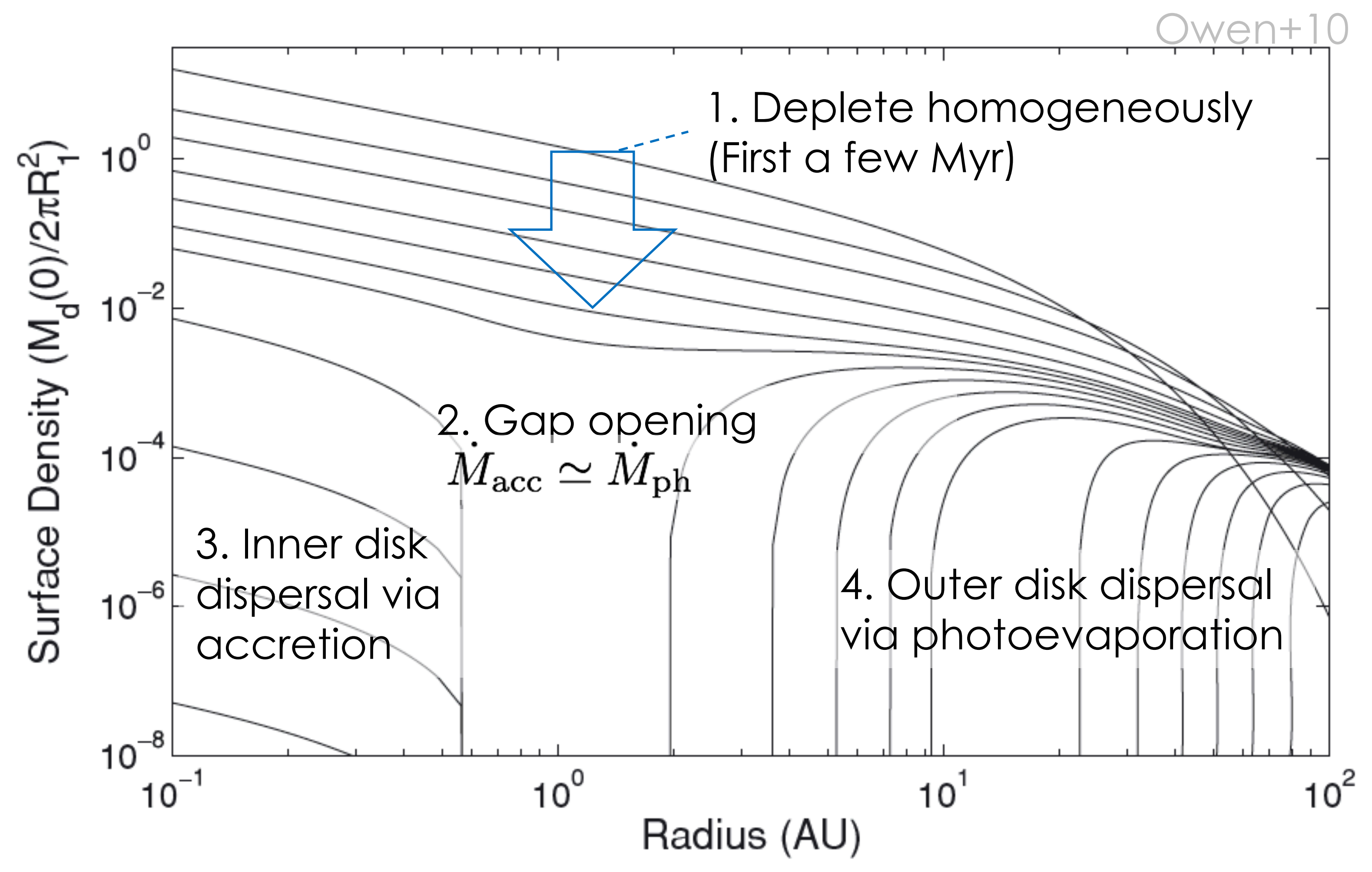
Mass-Loss Profiles



- Peaks at $R \sim \frac{GM_*}{c_s^2}$
- Decreases to larger distances

Viscous Evolution + Photoevaporation

Clarke+01, Alexander+06, Owen+10, Gorti+15



1. Deplete homogeneously (First a few Myr)

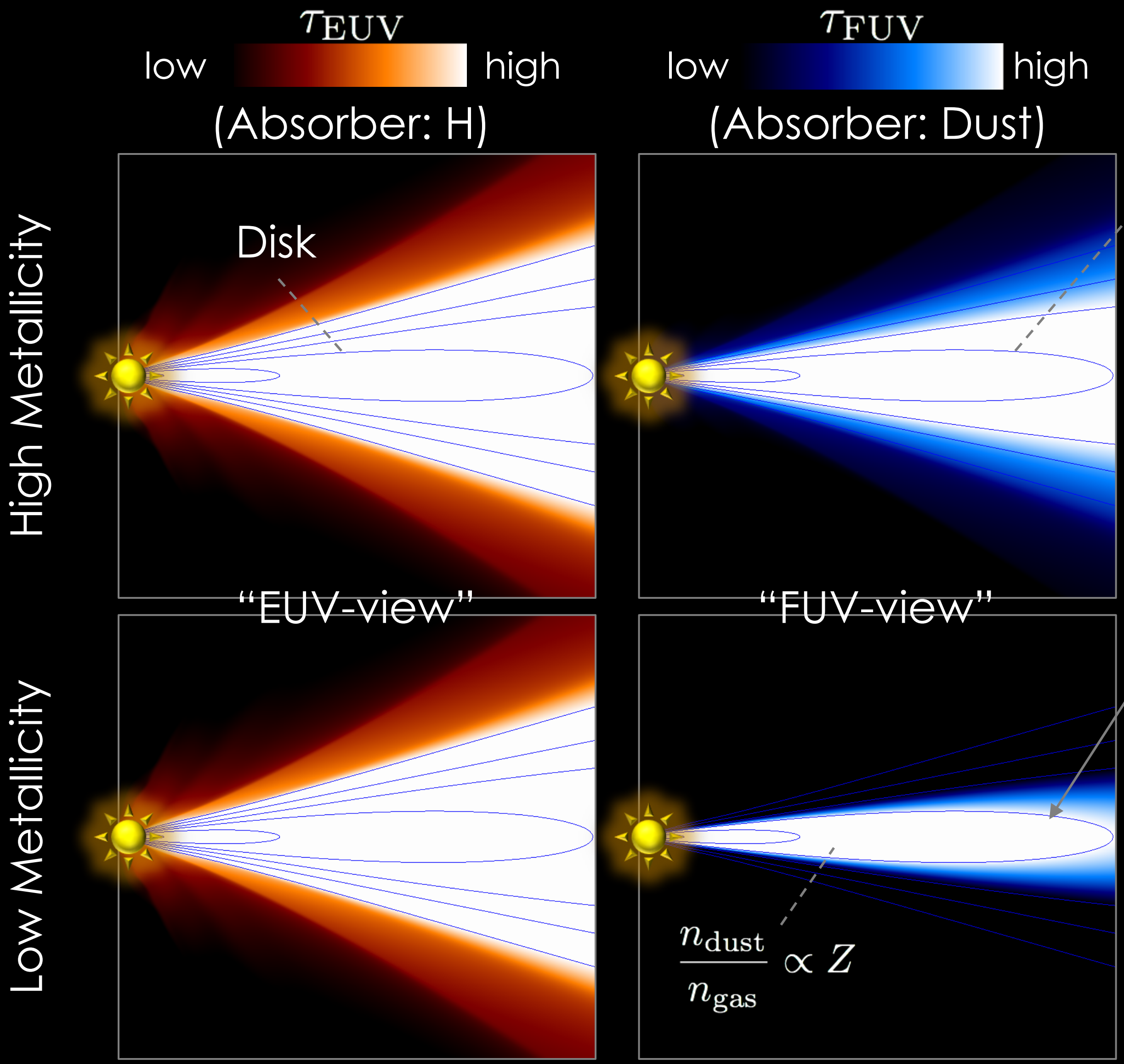
2. Gap opening $\dot{M}_{\rm acc} \simeq \dot{M}_{\rm ph}$

3. Inner disk dispersal via accretion

4. Outer disk dispersal via photoevaporation

Viscous Evolution + Photoevaporation well explains the two timescales

How could photoevaporation be Z-dependent ?

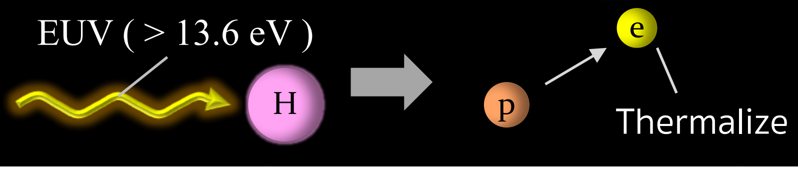


Blue solid lines:
Gas Density contours
(stratified structure)

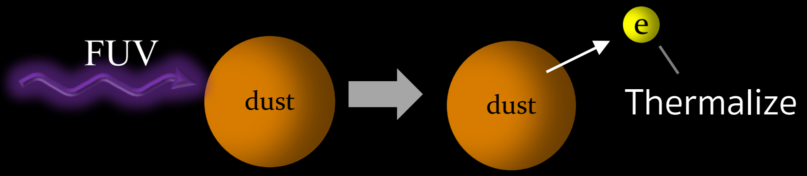
- Disks look the same to EUV.
- The optically thick region is embedded in the high **gas** density region.

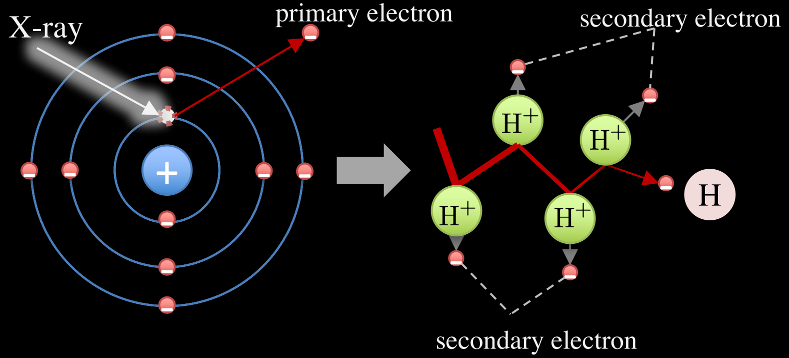
FUV can reach the deep interior with low-Z
→ yielding a higher mass-loss rate

Photoevaporation can be Z-dependent



	FUV	EUV	X-rays
Photon energy	6 eV ≦ $h\nu$ ≦ 13.6 eV	13.6 eV ≦ $h\nu$ ≦ 100 eV	0.1 keV ≦ $h\nu$ ≦ 10 keV
Main absorber	**Dust**	Atomic hydrogen	**Metal elements** (≳ 0.3 keV)
Penetrability	High	Low	High
Metallicity dependence	Dependent	Independent	Dependent

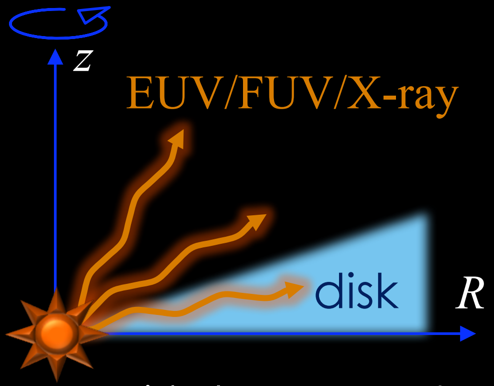




Our Aims:

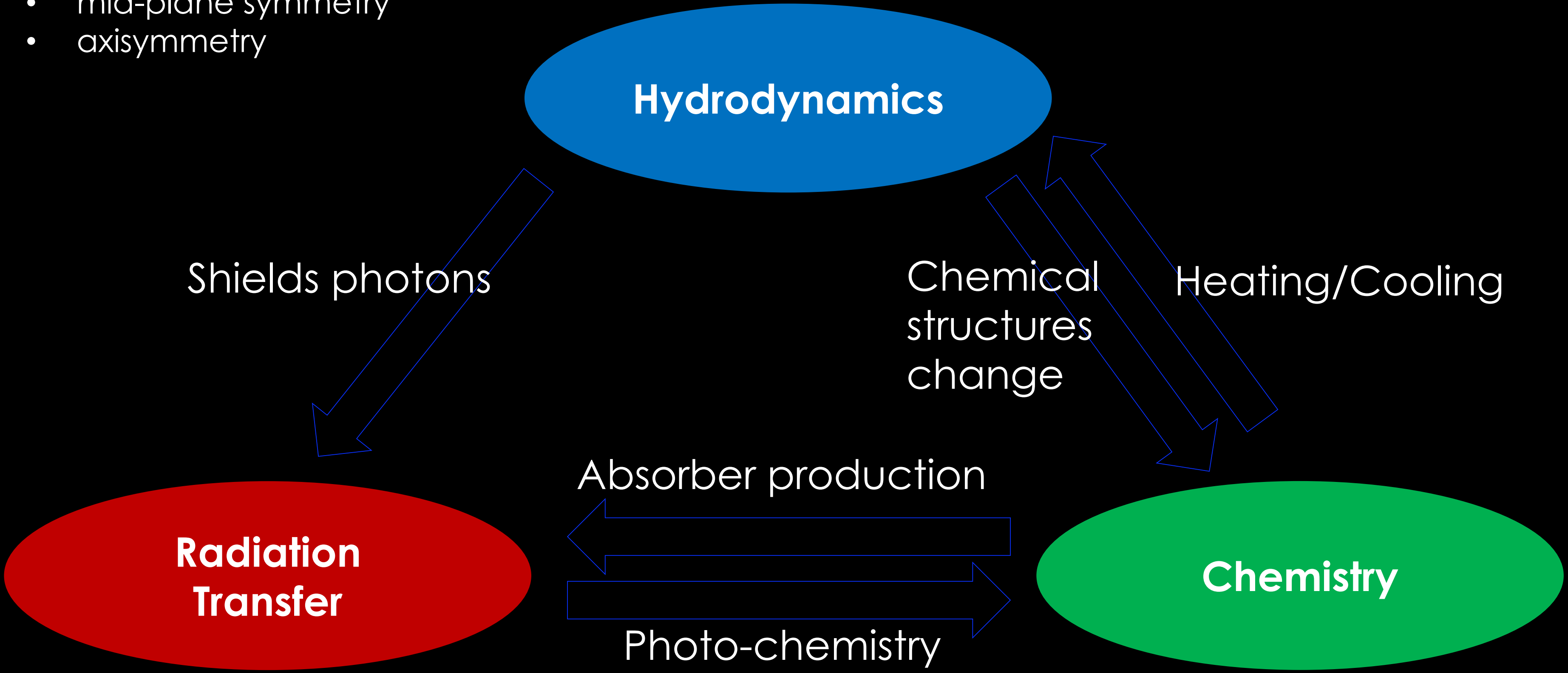
- To obtain metallicity dependence of mass-loss rates
- Giving implications to the observational lifetimes

Overview of the Calculation Methods



- mid-plane symmetry
- axisymmetry

Hydrodynamics (2D; spherical polar coord.)
\+ Radiation transfer (FUV/EUV/X-ray, dust IR)
\+ Nonequilibrium Chemistry



Comparison with (Selected) Previous Models

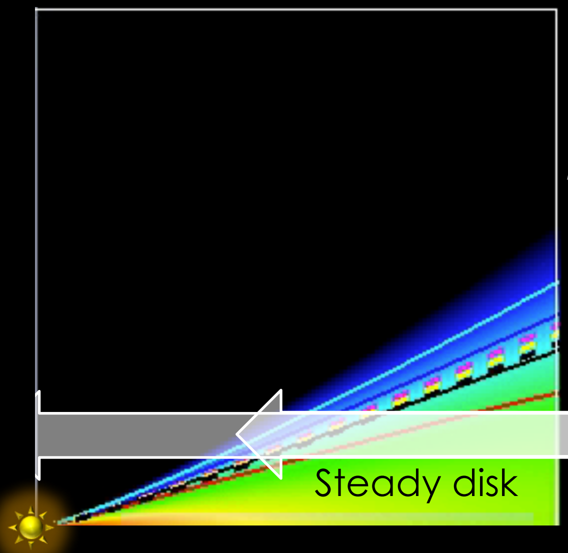
First self-consistent Rad.HD studies

	Hollenbach+94	Gorti+09	Owen+10	Ercolano+10	Wang+17	**Nakatani+18a**	**Nakatani+18b**
Hydrodynamics	No	No	Yes	No	Yes	Yes	Yes
Radiative transfer	Yes	Yes	No	Yes	Yes	Yes	Yes
Thermal processes	Yes	Yes	No	Yes	Yes	Yes	Yes
(Detailed) Chemistry	No	Yes	No	Yes	Yes	Yes	Yes
FUV heating	No	Yes	No	No	Yes	Yes	Yes
EUV heating	Yes	Yes	No	Yes	Yes	Yes	Yes
X-ray heating	No	Yes	Yes	Yes	Yes	No	Yes
Dust IR transfer	No	Yes	No	No	No	Yes	Yes
Multi-metallicity	No	No	No	Yes	No	Yes	Yes

UV Photoevaporation in Solar Metallicity Disk

(Nakatani +18a)

Density distribution



Dashed lines ($\tau_{\rm FUV}$)

Magenta:	0.5
Yellow:	1
Black :	2

Solid lines ($n_{\rm H}$ /cm^{-3})

Cyan: 10^5 Blue: 10^6

Black: 10^7 Red: 10^8

Photoevaporative flows launch at $\tau_{\rm FUV} \sim 1$ (base) (yellow dashed line)

EUV-driven ionized flow

$n_{\rm H} \sim 10^{3-5}\ {\rm cm}^{-3}$

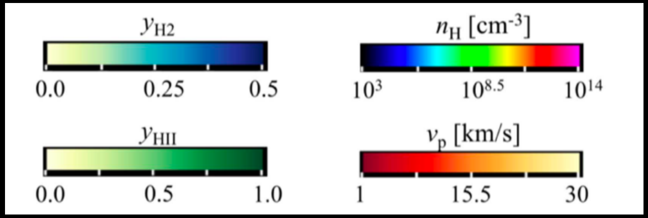
$v_{\rm p} \sim 5 - 30\ {\rm km/s}$

Dust-gas collisional cooling (blue region) is dominant at the base

FUV-driven neutral flow

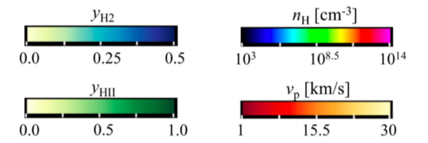
$n_{\rm H} \sim 10^{5-7}\ {\rm cm}^{-3}$

$v_{\rm p} \sim 0.5 - 5\ {\rm km/s}$

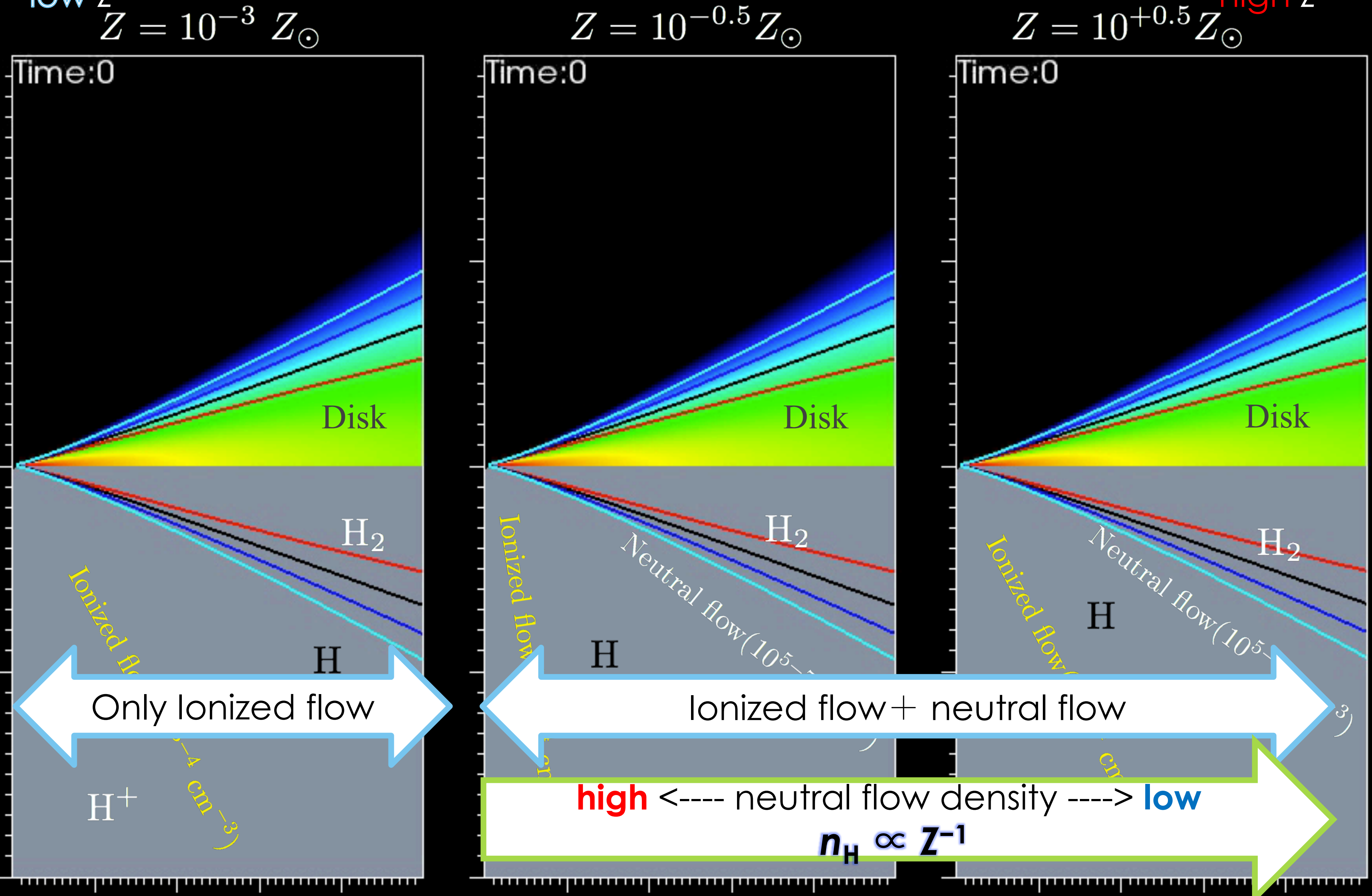


Color Scales

Various metallicities



low Z → high Z



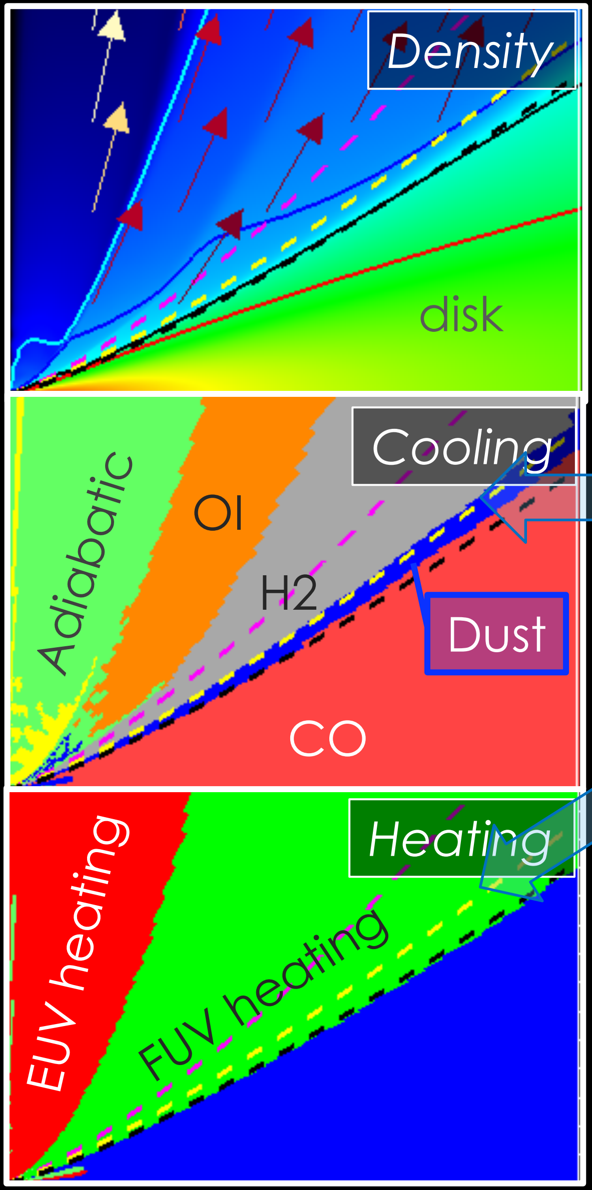
Only Ionized flow

Ionized flow + neutral flow

high <---- neutral flow density ----> **low**

$n_H \propto Z^{-1}$

No neutral flow at very low metallicity



FUV heating VS Dust-gas cooling
at the base ($\tau = 1$)

Dust-gas collisional cooling

$$\mathrm{collision\ rates} = 4\pi a^2 c_s n_{\mathrm{H}} n_{\mathrm{d}}$$

FUV heating

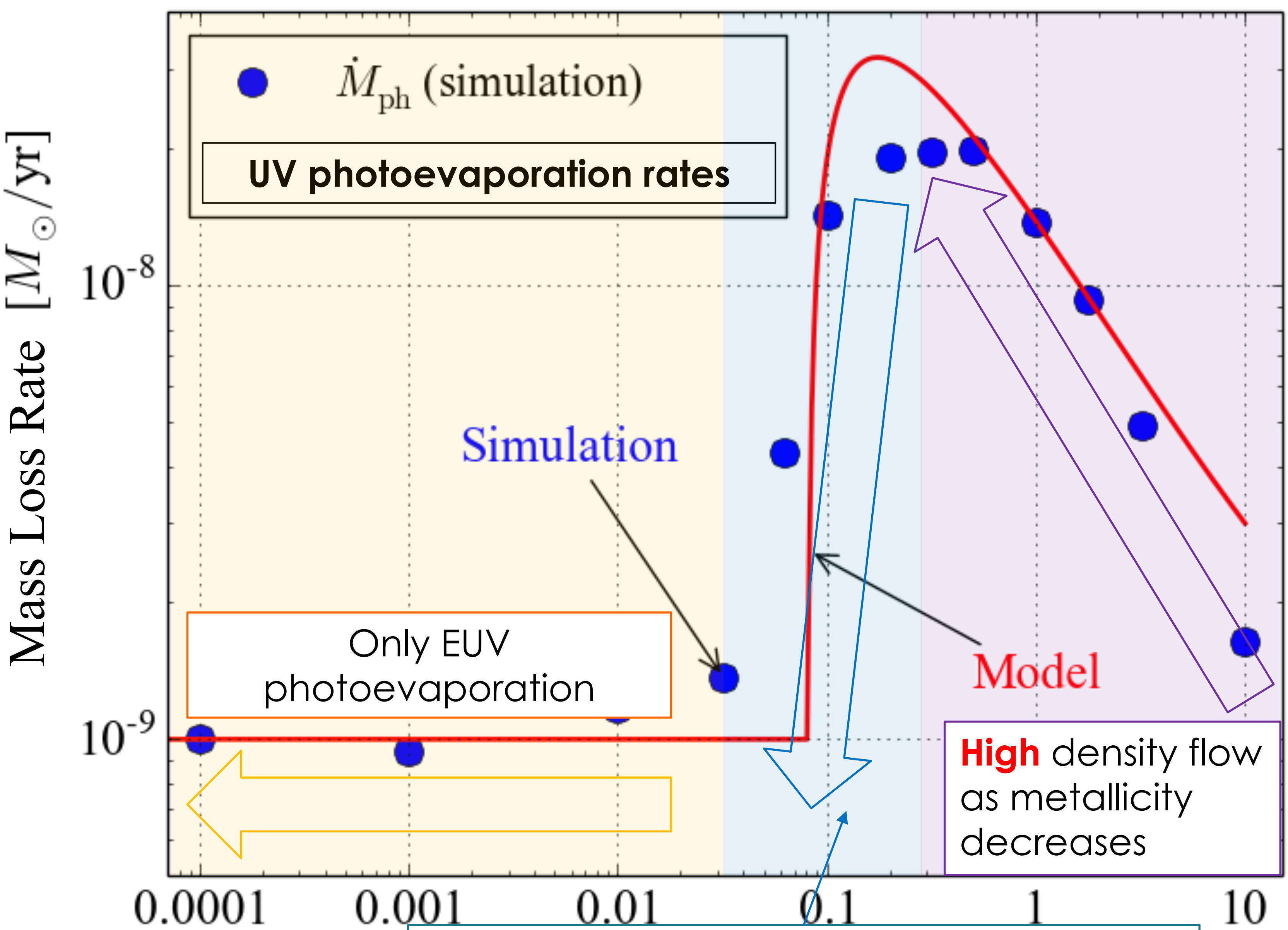
$$\mathrm{absorption\ rates} = F_{\mathrm{FUV}} \sigma_{\mathrm{d}} n_{\mathrm{d}}$$

$$n_{\mathrm{H,base}} \propto Z^{-1}$$

$$r = \frac{\mathrm{Cooling}}{\mathrm{Heating}} \propto \frac{a_{\mathrm{d}}^2 c_s n_{\mathrm{H}}}{F_{\mathrm{FUV}} \sigma_{\mathrm{d}}} \propto Z^{-1}$$

$$L_{\mathrm{FUV}} e^{-\tau_{\mathrm{FUV}}}$$

metallicity decreases ⇒ r increases.



UV photoevaporation rates

Only EUV photoevaporation

High density flow as metallicity decreases

FUV heating becomes **less efficient than cooling.** Neutral flow has less contribution to mass loss.

“X-ray Controversy”

Is X-ray effective to drive photoevaporation ?

Affirmative

- Ercolano+09
- Owen+10
- Ercolano & Clarke10

etc.

X-ray can yield $\dot{M}$ as high as $\sim 10^{-8}\,M_{\odot}\,\mathrm{yr}^{-1}$

Negative

- Alexander+04
- Gorti+09
- Wang & Goodman17

etc.

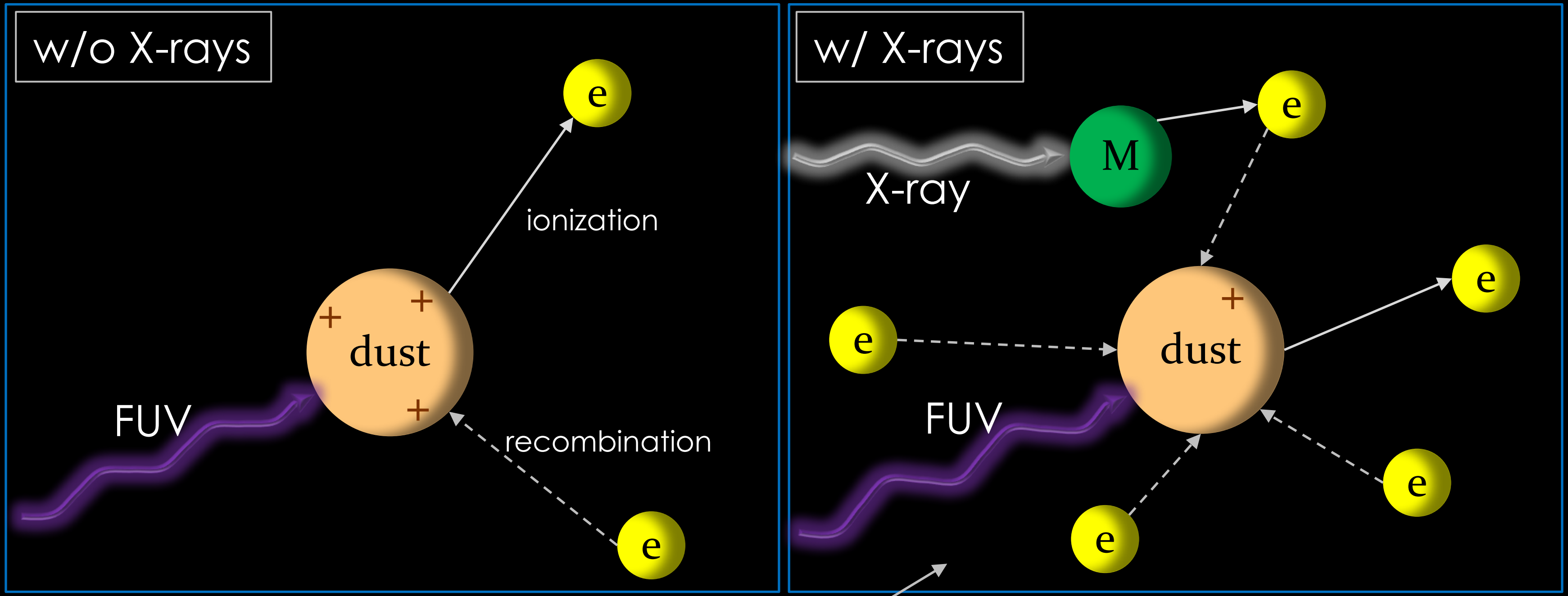
X-ray is ineffective or has only an indirect effect (next slide)

Problems in these studies:

- Almost all do not use a self-consistent calculation method.
- Wang & Goodman do, but X-ray is assumed to have a single energy (1keV)

X-rays strengthen the FUV heating

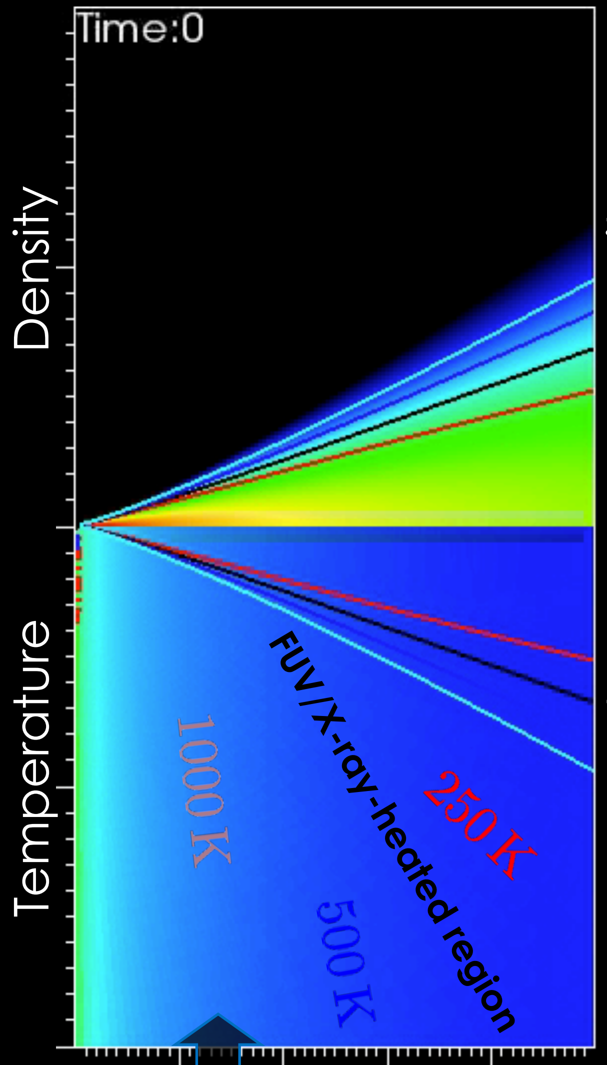
(Gorti & Hollenbach 2009)



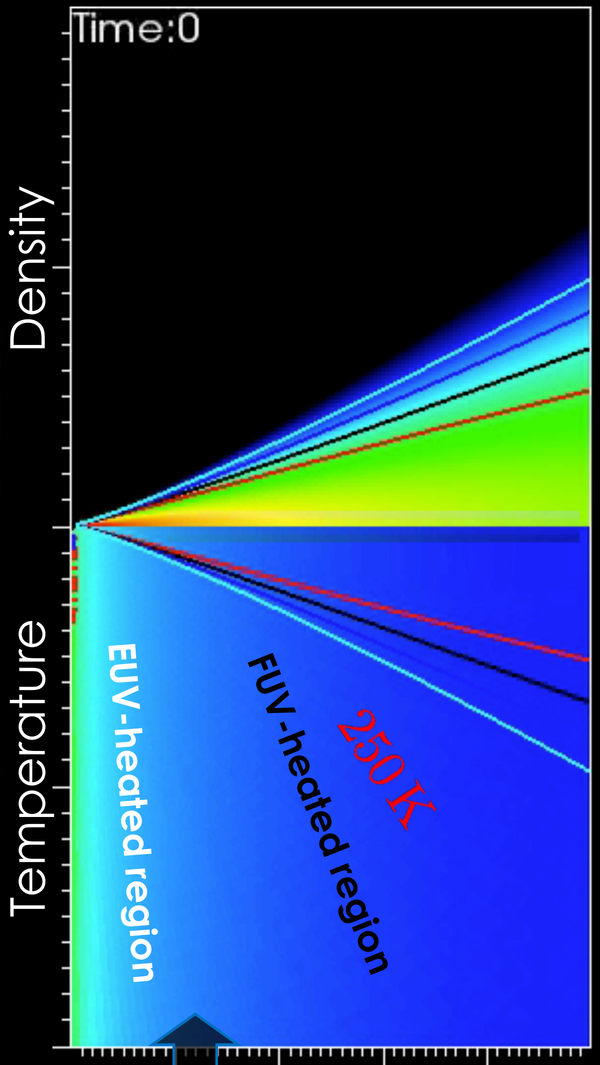
Electron rich
→ Efficient recombination
→ Reduced positive charge
→ Efficient photoelectron ejection
→ Strengthened FUV heating

X-ray Effects ($Z = 0.1\,Z_\odot$ disks ; Nakatani+18b)

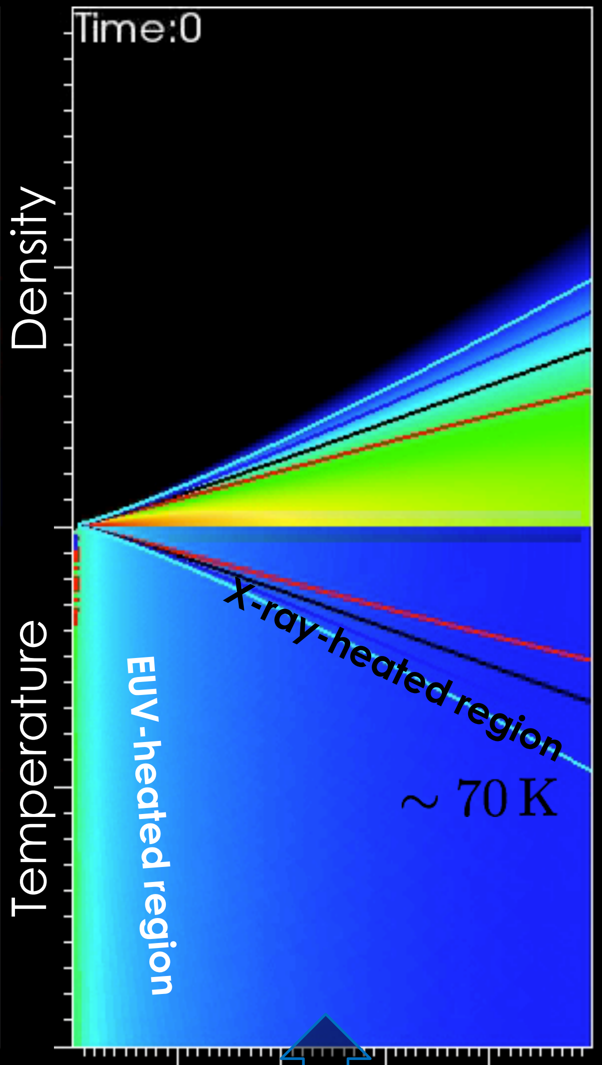
FUV/EUV/X-ray



FUV/EUV



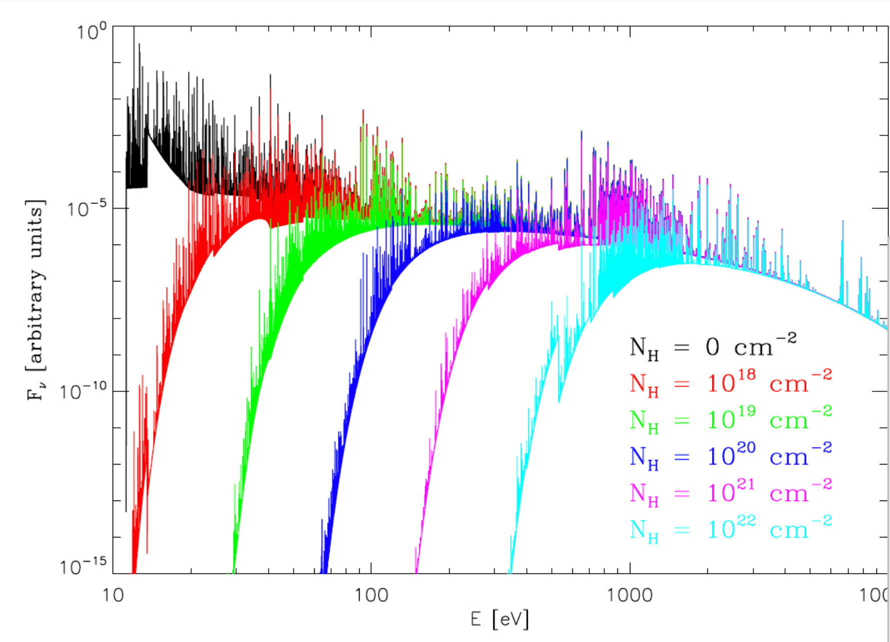
EUV/X-ray



- The temperature is higher in the left
- The gas evaporates more strongly in the left

X-ray doesn't excite flows

Is X-ray really an effective driver?



Ercolano et al. (2009)

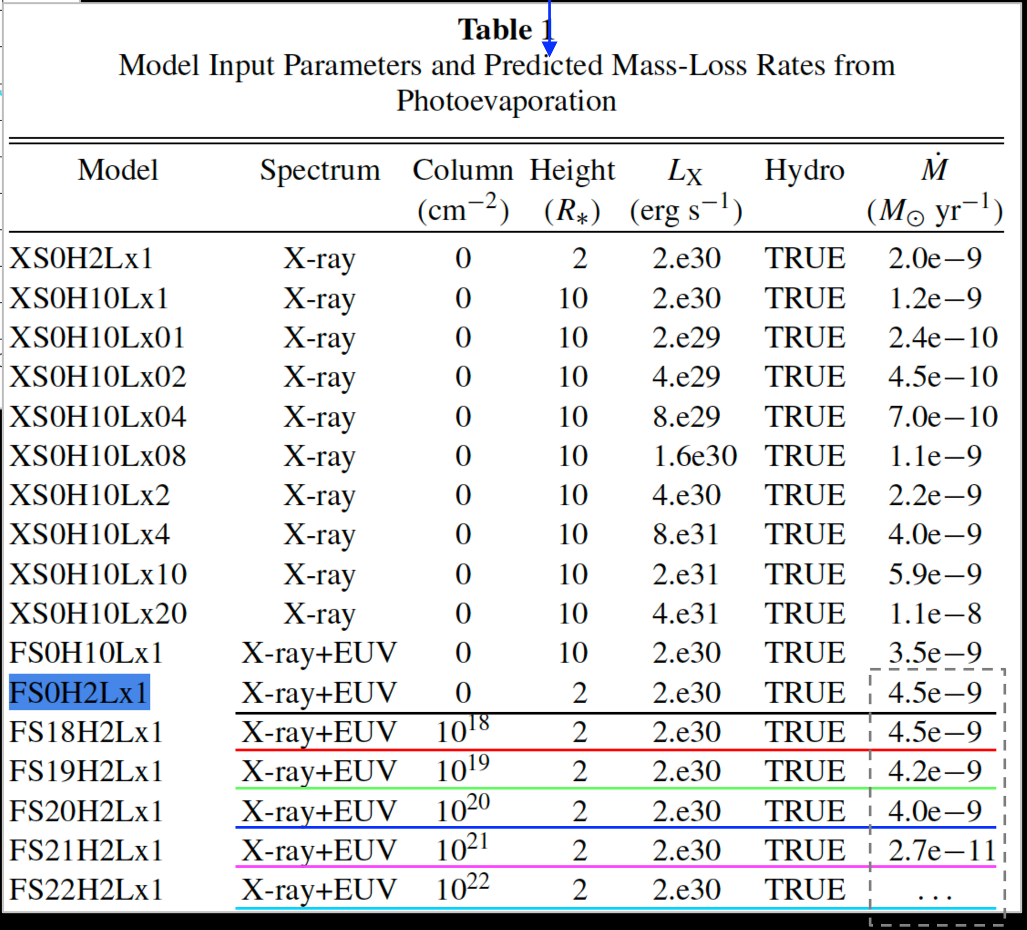


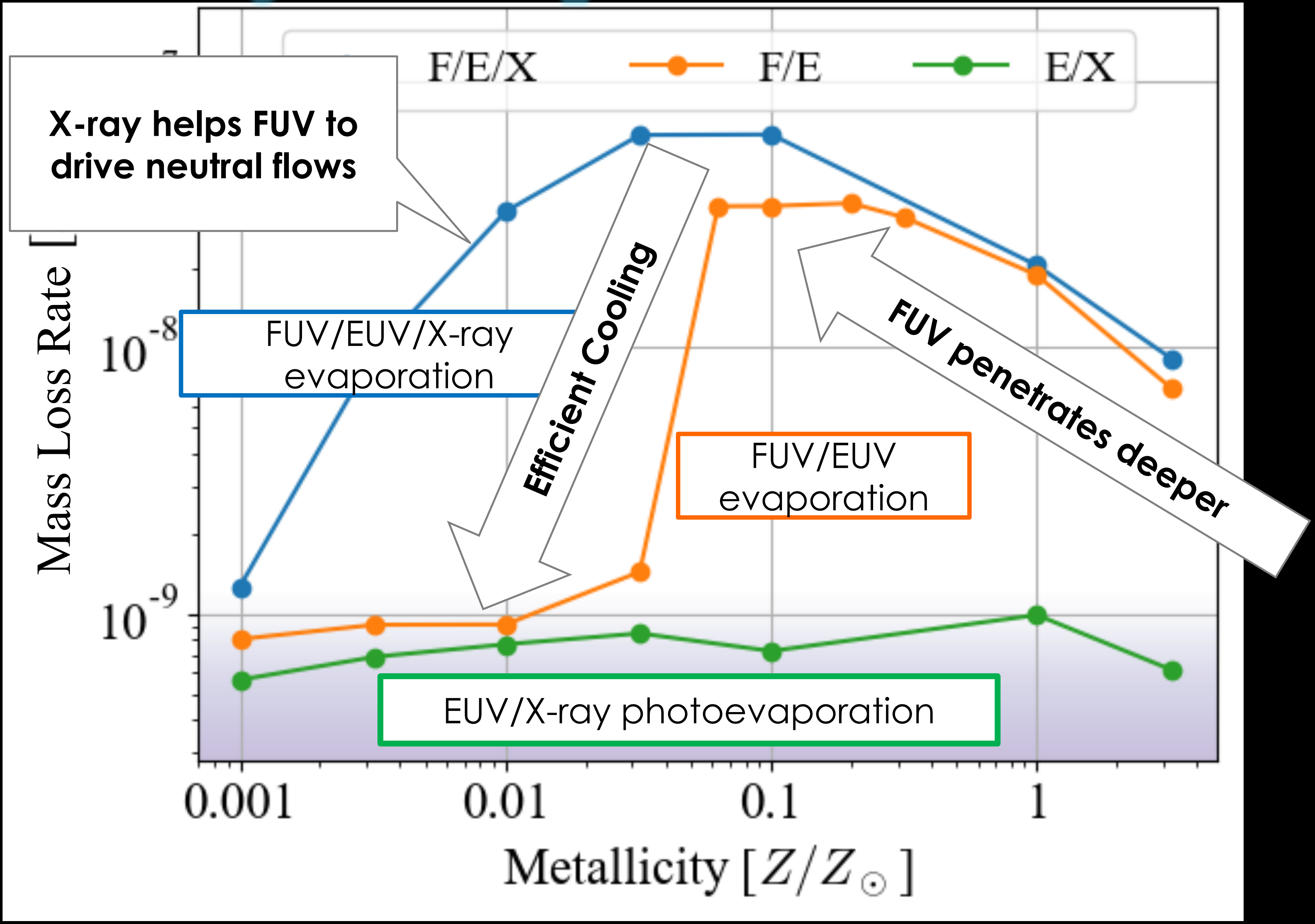
Table 1
Model Input Parameters and Predicted Mass-Loss Rates from Photoevaporation

Model	Spectrum	Column (cm^{-2})	Height (R_*)	L_X ($erg\ s^{-1}$)	Hydro	$\dot{M}$ ($M_\odot\ yr^{-1}$)
XS0H2Lx1	X-ray	0	2	2.e30	TRUE	2.0e−9
XS0H10Lx1	X-ray	0	10	2.e30	TRUE	1.2e−9
XS0H10Lx01	X-ray	0	10	2.e29	TRUE	2.4e−10
XS0H10Lx02	X-ray	0	10	4.e29	TRUE	4.5e−10
XS0H10Lx04	X-ray	0	10	8.e29	TRUE	7.0e−10
XS0H10Lx08	X-ray	0	10	1.6e30	TRUE	1.1e−9
XS0H10Lx2	X-ray	0	10	4.e30	TRUE	2.2e−9
XS0H10Lx4	X-ray	0	10	8.e31	TRUE	4.0e−9
XS0H10Lx10	X-ray	0	10	2.e31	TRUE	5.9e−9
XS0H10Lx20	X-ray	0	10	4.e31	TRUE	1.1e−8
FS0H10Lx1	X-ray+EUV	0	10	2.e30	TRUE	3.5e−9
FS0H2Lx1	X-ray+EUV	0	2	2.e30	TRUE	4.5e−9
FS18H2Lx1	X-ray+EUV	10^{18}	2	2.e30	TRUE	4.5e−9
FS19H2Lx1	X-ray+EUV	10^{19}	2	2.e30	TRUE	4.2e−9
FS20H2Lx1	X-ray+EUV	10^{20}	2	2.e30	TRUE	4.0e−9
FS21H2Lx1	X-ray+EUV	10^{21}	2	2.e30	TRUE	2.7e−11
FS22H2Lx1	X-ray+EUV	10^{22}	2	2.e30	TRUE	. . .

- Mass-loss rates decrease as the spectra get hard
- Sharp decline at $10^{20\text{-}21}$ cm^{-2}

> 100eV photons are less effective.
< 100eV is very effective.

UV/X-ray Photoevaporation Rates



X-ray helps FUV to drive neutral flows

FUV/EUV/X-ray evaporation

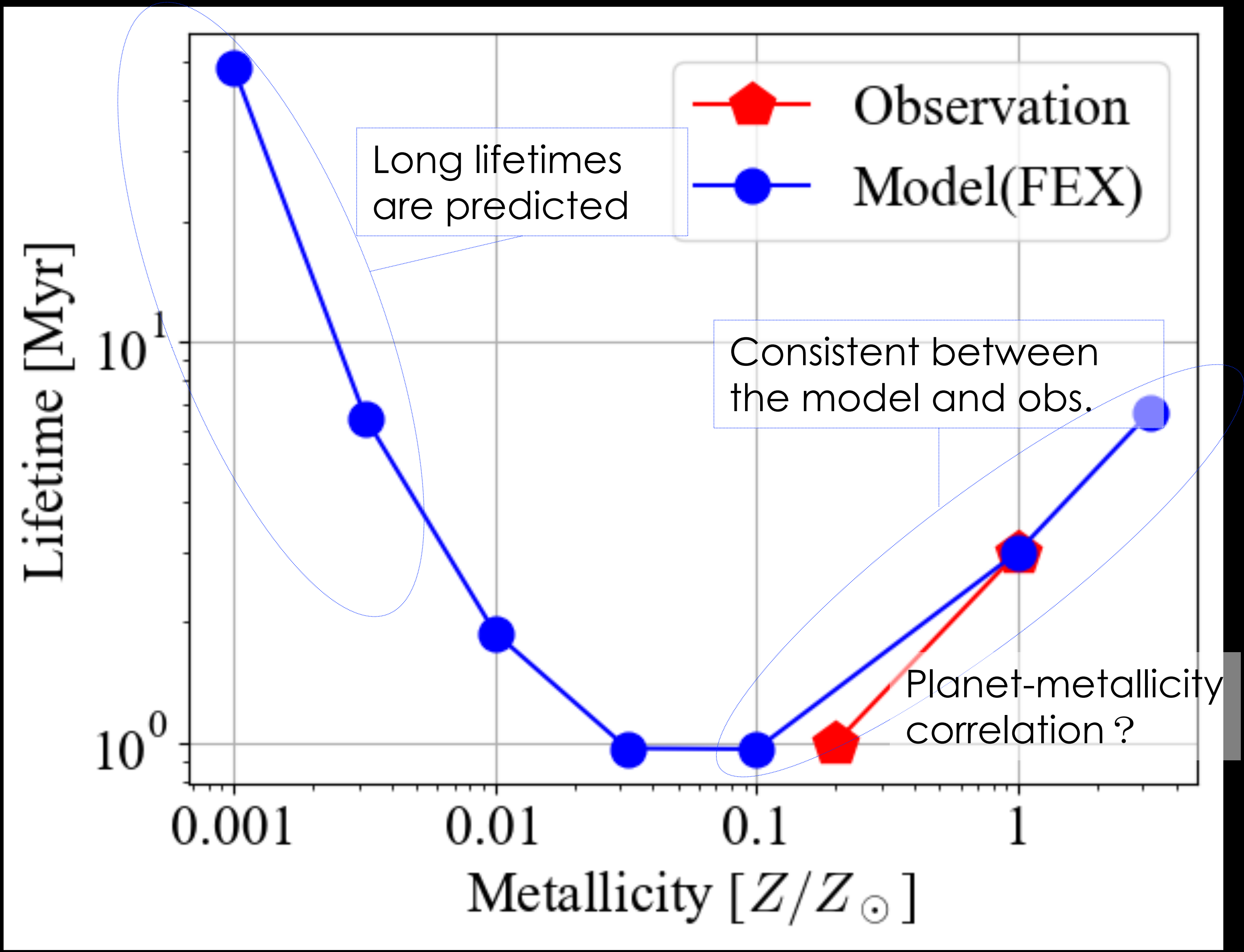
Efficient Cooling

FUV/EUV evaporation

FUV penetrates deeper

EUV/X-ray photoevaporation

Estimated Dispersal Times



Long lifetimes are predicted

Consistent between the model and obs.

Planet-metallicity correlation ?

- Summary
  1. Motivation: Observational metallicity dependence of lifetimes.
  2. Methods: Hydrodynamical simulations with radiative transfer and non-equilibrium chemistry to examine the metallicity dependence of photoevaporation.
  3. Results: Photoevaporation rates has a peak at $Z \sim 10^{-0.5} Z_\odot$. If X-rays are taken into account, the peak moves to $Z \sim 10^{-1} Z_\odot$. X-rays strengthen the FUV heating.
  4. Conclusion: Our model would be consistent with the observed metallicity dependence of the lifetimes, and it predicts that the disks would have even longer lifetimes in the much lower metallicity environments $Z \lesssim 10^{-2} Z_\odot$.

- Future Prospects of the Field
  - Luminosity dependence
  - Central-star-mass dependence
  - Dust dynamics
  - Interplay with MHD
  - Low-metallicity envirnments observations